*AKARI, a Light to Illuminate the Misty Universe*
*ASP Conference Series, Vol. 418, © 2009*
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# Observations of ULIRGs with the IRS on *Spitzer*

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**Abstract.** Ultraluminous Infrared Galaxies (ULIRGs), those systems with $L_{IR} \geq 10^{12} L_{\odot}$, have the power output of quasars, yet (re-)emit the vast majority of their energy in the far-infrared part of the spectrum. Because this energy is reprocessed by dust, the origin of the power is often hidden from view. With the Infrared Spectrograph on the *Spitzer Space Telescope*, we have observed a large number of low-redshift ULIRGs in order to better understand the source of their power, the conditions in the dusty interstellar medium, and their relationship to optically selected quasi-stellar objects (QSOs), effectively increasing the number of ULIRGs with rest-frame mid-infrared spectra by two orders of magnitude. The IRS has also been used to obtain the first mid-infrared spectra of samples of ULIRGs at redshifts of $z > 2$. In this paper, we summarize the key findings from the IRS studies of ULIRGs at low and high redshifts, and look toward the future of far-infrared spectroscopy from space.

## 1. Introduction

One of the most striking results to appear in the last decade has been the discovery that the masses of the central black holes and stellar bulges in galaxies are correlated (Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhart et al. 2000). The fact that in present-day galaxies the ratio of the mass of the stellar bulge to the central super-massive black hole has a constant value of about 700, implies that star formation and black hole accretion are intimately linked in the evolutionary history of a galaxy. Precisely how this relationship is built up over cosmic time is one of the key questions driving observational and theoretical astrophysics today.

Galaxies experiencing powerful bursts of star formation are usually blanketed in a great deal of dust. The most luminous star-forming galaxies have typically been discovered via their enhanced infrared emission (Soifer et al. 1984, 1986). These galaxies can emit more than 90% of their total energy in the far-infrared. Studies with ISO and *Spitzer* have shown that Luminous Infrared Galaxies (LIRGs – galaxies having infrared luminosities $L_{\rm IR} \geq 10^{11}\,{\rm L}_{\odot}$) account for about 50% of the co-moving infrared luminosity density at $z \sim 1$ (Caputi et al. 2007; Magnelli et al. 2009), with Ultraluminous Infrared Galaxies (ULIRGs—galaxies with infrared luminosities $L_{\rm IR} \geq 10^{12}\,{\rm L}_{\odot}$) making up an increasing fraction at higher redshifts. More than half of all the light emitted from stars is absorbed by dust and re-radiated in the infrared (Elbaz & Cesarsky 2003).

Models and observations of luminous starbursts and AGN suggest that periods of significant mass accretion onto a central black hole may also preferentially occur during episodes of enhanced nuclear star-formation (Soltan 1982; Yu &

Tremaine 2002; Hopkins et al. 2007). This seems to be borne out through studies of ULIRGs and QSOs at high redshift. Stacking of faint $1 < z < 3$ ULIRGs selected with *Spitzer* at 24 $\mu$m suggest a significant contribution from buried AGN to the total power emitted in the far-infrared (Papovich, et al. 2007; Daddi, et al. 2007). The recent discovery of resolved far-infrared [C II] emission in the $z = 6.42$ QSO SDSS J114816.6+52, suggests a star-formation rate of about 1700$M_\odot$ yr$^{-1}$ (Walter et al. 2009), providing further evidence for the link between black hole and stellar bulge growth at extremely high-redshift.

Nearly all low-redshift ULIRGs are interacting or merging, late-type galaxies. ULIRGs have intense, compact nuclear starbursts and many appear to harbor (buried) AGN. Some ULIRGs have such intense nuclear star-formation that they also drive winds of hot gas into the galactic halo. In the simplest model of ULIRG evolution, a merger triggers an intense starburst and the fueling of a nascent AGN. The earliest stages are starburst-dominated with cool far-infrared colors. As the molecular fuel is used up and the AGN begins to dominate the emission, the far-infrared colors become warmer, eventually revealing the central QSO as the dust is cleared through the action of SNe and the AGN itself (see Sanders & Mirabel 1996 for a review).

An important question has always been the nature of the dominant energy source powering the dust emission in ULIRGs. How many ULIRGs are AGN dominated, how many are starburst dominated, and how many are composite systems (with a significant contribution from young stars and a central AGN)? Are the relative fractions consistent with the simple model of their evolution? Do these fractions evolve with redshift, and are the basic properties of low-redshift ULIRGs similar to those at high-redshifts?

## 2. Low-Redshift ULIRG Spectroscopy with *Spitzer*

The sensitivity and broad mid-infrared wavelength coverage of the Infrared Spectrograph (IRS—see Houck et al. 2004) has provided us with the opportunity to study large numbers of low-redshift LIRGs and ULIRGs. There are a number of advantages of the mid-infrared for addressing some of the fundamental questions regarding ULIRGs. Compared to the visual, the extinction in the mid-infrared is greatly reduced, and there are numerous atomic, fine-structure lines (e.g., [Ne II], [Ne III], [Ne V], [O IV], [S III]) that are effective diagnostics of the radiation field. In particular, since the ionization potential of $Ne^{++++}$ is 97 eV, this usually signals the presence of an AGN in the spectrum of a galaxy. In addition, pure rotational lines of $H_2$ are available as direct probes of the warm (100-400 K) molecular gas. Finally, aromatic features (Poly-cyclic Aromatic Hydrocarbons) are abundant, the strongest being at 6.2, 7.7, 8.6, 11.3, 12.7, and 17 $\mu$m. These small grains are easily destroyed in the harsh radiation fields surrounding an AGN, yet are ubiquitous in star-forming galaxies. The fine-structure line ratios together with the PAH features provide a powerful diagnostic of the dominant energy source in a dusty galaxy, first demonstrated effectively with data from the Infrared Space Observatory (Genzel, et al. 1998; Sturm et al. 2002).

Well over 100 low-redshift ULIRGs have been observed with the IRS on *Spitzer* (Armus et al. 2004,2006,2007; Higdon, et al. 2006; Desai et al. 2007, Spoon et al. 2004, 2007; Imanishi et al. 2007; Farrah et al. 2007). The most striking aspect of the low-resolution (Short-Low and Long-Low) spectra is there diversity. The mid-infrared spectra of ULIRGs range from nearly featureless, power-law spectra (with and without silicate absorption) to those that are dominated by very strong PAH and fine-structure line emission. In the low-resolution spectra, PAH emission, and $H_2O$, hydrocarbon, and silicate absorption are the dominant spectra features. In many of the low-resolution spectra, the fine-structure lines of [Ne II] 12.8 $\mu$m , [Ne III] 15.5 $\mu$m, [O IV] 25.9 $\mu$m, [S II] 18.7, 33.4 $\mu$m, and [Si II] 34.8 $\mu$m can also be seen. The power-law spectra are most easily explained as produced in ULIRGs where an AGN dominates the mid-infrared emission. The PAH-rich spectra are produced in ULIRGs where star-formation dominates. From the silicate absorption at 9.7 and 18 $\mu$m, the implied visual extinctions range from undetectable, to $A_V > 80$ mag. The strength of the silicate absorption also appears correlated with the 6.2 $\mu$m PAH equivalent width (EQW), such that ULIRGs with low PAH EQW can have either very small or very large silicate absorption (Spoon et al. 2007). The lack of a significant number of ULIRGs with intermediate silicate absorption depth at low PAH EQW might indicate a short timescale for this partially obscured stage, once the hot dust becomes visible.

The mid-infrared spectra of ULIRGs roughly correlate with the optical classification. Sources that are classified based upon their optical emission line ratios as Seyferts have smaller PAH EQW, on average, than sources which are classified as starbursts (Desai et al. 2007). The Seyfert ULIRGs have a median 6.2 $\mu$m PAH EQW of 0.04 $\mu$m, while the starburst ULIRGs have a median 6.2 $\mu$m PAH EQW of 0.28 $\mu$m. ULIRGs that are optically classified as LINERs fall in between, having a median 6.2 $\mu$m PAH EQW of 0.11 $\mu$m. Similarly, ULIRGs which are classified as "cold" in the far-infrared (ratio of IRAS $f_{25}/f_{60} < 0.2$) have a median 6.2 $\mu$m PAH EQW (0.24 $\mu$m) which is significantly larger than that seen in "warm" ULIRGs (0.04 $\mu$m). While there is rough consistency between optical and mid-infrared spectral types, there are important differences among individual sources, the classes as a whole . For example, the median 6.2 $\mu$m PAH EQW among the ULIRGs that are optically classified as starbursts, is only about half as large as that seen in pure starburst galaxies of lower luminosity (Brandl et al. 2006).

There are also trends of the PAH EQW with luminosity among ULIRGs. The lowest luminosity sources tend to have the largest PAH EQW, closest to that seen in pure starburst galaxies, while the most luminous sources have the smallest PAH EQW (Desai et al. 2007). This trend had also been seen in the ISO data (Tran et al. 2001). The low PAH EQW in the most luminous ULIRGs is consistent with an excess of hot dust in these galaxies. The relation, although it has a large scatter, can be fit by $\log_{10}$[6.2 $\mu$m PAH EQW ( $\mu$m)] = $(7.71 \pm 0.07) + (-0.723 \pm 0.006) \times \log_{10}(\nu L_{24})[L_\odot]$.

The IRS high-resolution data show that about 40% of the ULIRGs show [NeV] emission. The faintest lines confidently observed have fluxes around $10^{-21}$W cm$^{-2}$, and line flux ratios of [NeV] 14.3/[NeII] 12.8 = 0.01 (Armus et al. 2007; Farrah et al. 2007). The fraction of the luminosity generated by an AGN as calculated from either the [NeV] or [OIV] emission lines is often significantly lower than implied by the 6.2 $\mu$m PAH EQW, or $L_{PAH}$ / $L_{IR}$. About 10% of the sources with detectable [NeV] emission are classified as starbursts in the optical, while the rest are either LINERs or Seyferts. Interestingly, [NeV] emission is detected even in some sources that are optically thick as measured in the X-rays (e.g. NGC 6240, UGC 5101), and it is not seen in some sources that are type-1 AGN in the optical (e.g. Mrk 231).

Although the 6.2 $\mu$m PAH EQW is an extremely effective diagnostic of the importance of an AGN to the mid-infrared spectrum, the total to mid-IR emission and the PAH band ratios vary from ULIRG to ULIRG. By measuring all the PAH features and the total IR emission from the ULIRGs, we can estimate the fraction of the total energy generated by young stars. When the full ULIRG spectral energy distributions are fit according to the method outlined in Marshall et al. (2007), the ratio of total PAH to IR luminosity can be measured for each source. The result is shown in Figure 1. The $L_{PAH}/L_{IR}$ ratio in ULIRGs ranges from about 0.004 to 0.09 in the sample. Arp 220 has the lowest value, while IRAS 18030+0705 has the largest. Since the bolometric energy in ULIRGs is dominated by the infrared, this is equivalent to the fraction of the total power produced by young stars. If we look at the ULIRGs as a class, and compare them to pure starburst galaxies, the median value of $L_{PAH}/L_{IR}$ suggests that approximately 40-50% of the energy of a typical ULIRG is generated from a starburst. Studies of PG QSOs (Schweitzer et al. 2006, 2008) also suggest that up to 30% of the far-infrared luminosity could be generated by a starburst, but in these systems, this only accounts for a few percent of the bolometric luminosity.

Although it has been known for quite some time that ULIRGs can drive powerful outflows (e.g., Heckman, Armus & Miley 1990; Heckman et al. 2000), the IRS high-resolution data has recently been used to penetrate the dust in IRAS F00183-7111 and give us a glimpse of the high-velocity gas and shocks at the base of a superwind (Spoon et al. 2009).

The IRS data have also given us a glimpse of the properties of the warm molecular gas, the dust, and the dense interstellar medium in ULIRGs as revealed in the mid-infrared. The pure rotational $H_2$ lines have been detected in about 80% of the ULIRGs studied (Higdon et al. 2006). The average warm molecular gas mass is about $2 \times 10^8 M_\odot$, and the warm/cold molecular gas mass ratio is typically less than about 1% (although there is a large range). The mean H2-to-IR luminosity ratio (summing over the $H_2$ seen in the mid-infrared) is about $10^{-4}$. Evidence for grain processing, in the form of crystalline silicates (e.g., forsterite) have been found in a dozen local ULIRGs (Spoon et al. 2006). The crystallinity (defined as the crystalline to amorphous ratio) is about 0.1, or about an order of magnitude higher than in the ISM of the Milky Way. One possible interpretation of this large crystalline fraction seen in ULIRGs is that cosmic-ray amorphization is lagging injection by evolved stars, pointing to a very recent episode of vigorous star formation. Dense ($n > 3 \times 10^6$ cm$^{-3}$), warm (200-700 K) molecular gas has been seen in absorption in some deeply obscured ULIRGs, in both AGN and starburst types (Lahuis et al. 2007). Column densities are $10^{15} - 10^{17}$ cm$^{-2}$ in $C_2H_2$, HCN, and $CO_2$. The relatively low temperatures and high abundances, as compared to YSOs, may imply deeply embedded, confined star-formation in these objects.

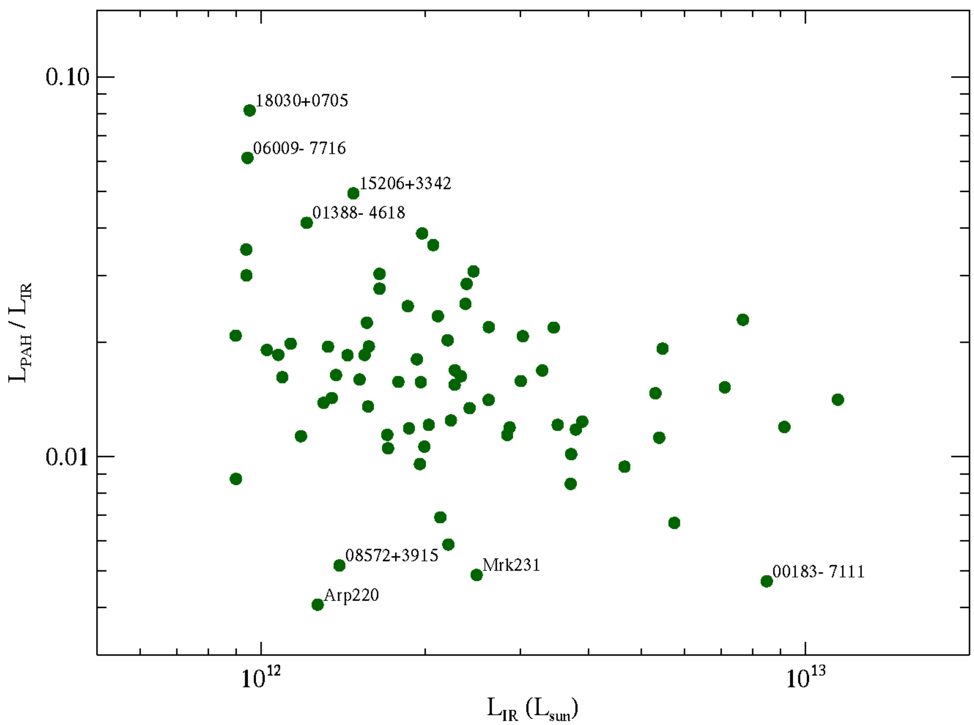


Figure 1. Total PAH to IR ($8-1000$ $\mu$m) luminosity ratio for local ULIRGs. The ULIRGs with the largest and smallest ratios are labeled.

## 3. High-Redshift ULIRG Spectroscopy with *Spitzer*

There have been a number of programs targeting high-redshift ULIRGs with the IRS. These sources have been selected in a wide variety of ways, from the sub-millimeter to the near-infrared. Although the numbers of galaxies observed is still relatively small (compared to the numbers observed a low-redshift) some interesting trends, and some surprises, are already evident.

The majority of bright, 24 $\mu$m-selected sources (those with $f_{24} \geq 0.5$ mJy) between redshifts of $1 < z < 3$ appear to be AGN-dominated (Houck et al. 2005; Sajina et al. 2007,2008; Yan et al. 2007). These sources typically have power-law IRS spectra, with little or no PAH emission. This AGN "bias" is easily understood, since an excess of hot dust makes AGN-like ULIRGs appear brighter in the observed mid-infrared bands at these redshifts. However, this selection effect has been overcome through a variety of means in *Spitzer* IRS spectral surveys by selecting (1) fainter sources ($f_{24} < 0.3$ mJy), (2) on color (based on IRAC, MIPS together with optical magnitudes, or by using IRAC colors to select sources with strong, rest-frame near-infrared stellar "bumps"), (3) sources with high infrared-to-X-ray ratios, and (4) sub-millimeter galaxies. Recent surveys of high-redshift ULIRGs with the IRS selected on these criteria (Pope et al. 2008; Valiante et al. 2007; Sajina et al. 2007; Teplitz et al. 2007; Farrah et al. 2008; Menendez-Delmestre et al. 2009; Desai et al. 2009) have uncovered samples with very strong PAH emission, indicating extremely powerful starbursts.

The IRS spectra of these high-redshift sources usually don't reflect that of the average local ULIRG. This is understandable, given the strong selection effects in the samples and the practical observing limits for the IRS. Observations of sources well below 0.5 mJy at 24 $\mu$m take many hours to complete, and the strongest PAH features as well as the silicate absorption feature are pushed out of the best part of the IRS band for $z > 3 - 3.5$.

However, there do seem to be some real differences between the high and low-redshift ULIRG spectra. Very luminous starbursts (those with large PAH EQW and $L_{IR} > 10^{13} L_{\odot}$) are absent from local samples, but are seen at high redshift among the sub-millimeter and bump-selected populations. These objects fall well above the trend between 6.2 $\mu$m PAH EQW and 24 $\mu$m luminosity seen among the low-redshift ULIRGs (Desai et al. 2007). At low-redshift, these extremely luminous sources are almost always AGN-dominated. Perhaps not surprisingly, this is not the case at $z \sim 2$, and we see evidence for this in the IRS spectra. The ratio of the 7.7 $\mu$m PAH to IR luminosity in the $z \sim 2$ sub-millimeter galaxies appears to follow the relation seen in local, low-luminosity starbursts (and the starburst-dominated ULIRGs). Also, the apparent optical depths, as measured in the silicate absorption features, for many of the luminous, starburst-dominated sub-millimeter galaxies appear significantly lower, on average, than those seen in local ULIRGs that are also starburst-dominated (Pope et al. 2008; Menendez-Delmestre 2009). This may indicate more distributed star-formation in these sub-millimeter galaxies. In a study of sub-millimeter selected, $z = 2$ QSOs, Lutz et al. (2008) find over 70% with PAH emission, implying star formation rates of $20 - 3000 \mathrm{M}_{\odot}\ \mathrm{yr}^{-1}$, further strengthening the connection between black hole growth and rapid star formation at high-redshift.

## 4. The Future of Far-Infrared Spectroscopy from Space

It is believed that the gas which gives rise to the first generation of stars cools through emission lines of $H_2$ (Santoro & Shull 2006). After the massive first generation stars explode as supernovae, injecting heavy elements into their surroundings, cooling of the gas is dominated by infrared fine-structure lines. The [C II] 158 $\mu$m and [O I] 63 $\mu$m lines are often the brightest single lines in the spectrum of a star-forming galaxy, each emitting up to 1% of the total FIR luminosity (Malhotra et al. 1997; Luhman et al. 1998) and providing a direct and accurate measure of the star formation rate. In galaxies with the most intense starbursts, the [O I] or even the [O III] 88 $\mu$m line can surpass [C II] as the primary coolant because of their higher critical densities (Brauher et al. 2008). At the highest redshifts, there is already an indication of a large range in the measured [C II] / FIR ratio in galaxies with extreme star formation rates (Walter et al. 2009; Maiolino et al. 2009).

With the completion of a number of infrared and sub-millimeter telescopes (*WISE, Herschel, SOFIA, JWST, CCAT, ALMA*), we will see great advances in our understanding of the dusty Universe. However, the ability to perform high-sensitivity, broadband, FIR spectroscopy will be lacking. The *Herschel* observatory will, for the first time, measure the cooling lines from a large sample of nearby galaxies and the most luminous sources at high-redshift, but it's ability to measure faint spectra lines from the majority of distant galaxies is limited because it is not cryogenically cooled. For example, the [C II] and [O I] lines in LIRGs at $z = 1$ and ULIRGs at $z = 2 - 3$ should have fluxes of about $10^{-19}$ W m$^{-2}$. The rest-frame mid-infrared lines ([Ne II], [Ne III], [Ne V], and [O IV]) will have line fluxes that are an order of magnitude fainter. Therefore, the brightest FIR cooling lines, and the most important mid-infrared diagnostic features will be at least $1 - 2$ orders of magnitude fainter than the practical limits of *Herschel* or *SOFIA*, for all but the most luminous galaxies at $z > 1$.

The *James Webb Space Telescope (JWST)* will provide our first glimpse of the earliest galaxies. However, most of the mid-infrared diagnostic lines will pass out of the observable range of the spectrographs ($\lambda < 30$ $\mu$m) by $z \sim 2$. The Atacama Large Millimeter Array (ALMA) will be extremely sensitive for spectral line observations of distant galaxies in the rest-frame far-infrared, following up known sources and objects newly discovered with surveys done with *WISE, Herschel, CCAT, LMT* and other far-infared and sub-millimeter telescopes. With its milli-arcsecond spatial resolution, it will provide a measure of the size and temperature profile of the FIR-emitting regions in high-redshift galaxies and quasars. However, being ground-based, it will operate only in limited atmospheric windows, rendering large redshift slices, inaccessible.

To be able to measure the rest-frame FIR cooling lines in galaxies that dominate the IR background at $z \sim 1$, and also measure the full suite of rest-frame mid-infrared atomic and molecular gas and dust features in high-redshift ULIRGs, a broadband, FIR spectrometer capable of reaching the natural astrophysical background over the $30 - 500$ $\mu$m range is required. The required sensitivity and wavelength coverage is impossible to reach from the ground, but could be achieved with a large, actively-cooled telescope in space. In our recently released 2008/2009 community plan for far-infrared/sub-millimeter astronomy from space (http:www.ipac.caltech.edu/DecadalSurvey/farir.html) we argue that US participation in the Japanese-led *Space Infrared Telescope for Cosmology and Astrophysics* (*SPICA*) mission is a high priority for the next decade. *SPICA* is a 3.5m, cryogenically cooled, FIR telescope planned for a 2017 launch, which provides an important and necessary technological and scientific step toward a large (6-10m) US-led single aperture FIR telescope, or space-based interferometer in the following decade. The proposed Background Limited Infrared Sub-millimeter Spectrometer (BLISS: see http:www.ipac.caltech.edu/ DecadalSurvey/BLISS_decadal_final.pdf) for *SPICA* bridges the gap, in wavelength and sensitivity space, between *JSWT* MIRI and *ALMA* (see Figure 2).

## 5. Conclusions

*Spitzer* IRS spectroscopy has revealed an unusually large diversity in the rest-frame mid-infrared spectra of ULIRGs. This is undoubtedly reflecting a wide variety of physical conditions in these extreme objects. The fact that many ULIRGs and QSOs appear composite in nature, provides evidence for periods of both rapid stellar mass buildup and black hole growth in dusty galaxies. *Spitzer* has also given us our first look at the rest-frame mid-infrared spectral properties of samples of high-redshift ULIRGs and QSOs, strengthening the link between

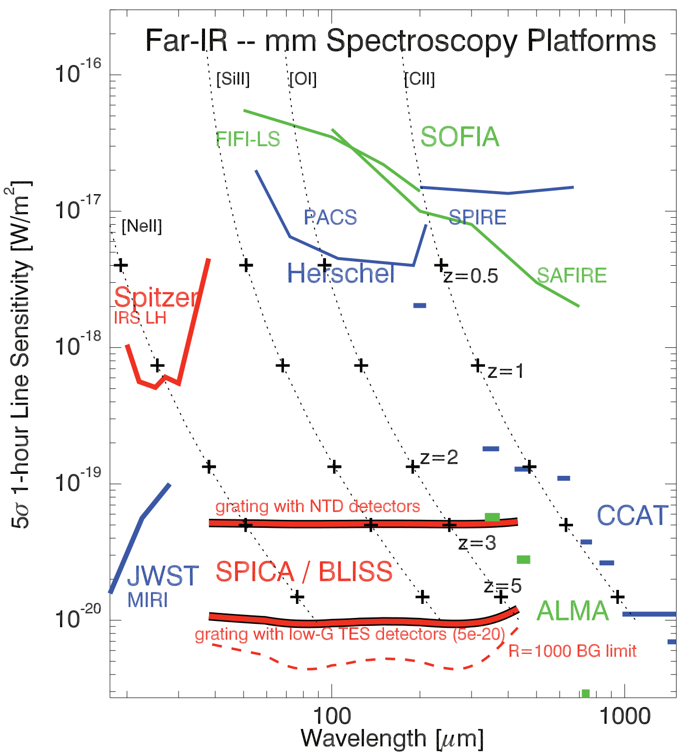


Figure 2. Anticipated performance of the Background Limited Infrared Sub-millimeter Spectrometer (BLISS) on the Japanese-led *SPICA* mission, compared to other existing or anticipated far-IR/sub-mm platforms. *SPICA*/BLISS would have continuous coverage from $38 - 433$ $\mu$m, and be $2-3$ orders of magnitude more sensitive than *Herschel* or *SOFIA*. Also shown are the expected fluxes for a few key infrared emission lines from a ULIRG at $0.5 < z < 5$ illustrating how BLISS will enable measurement of these key features at the earliest epochs.

starbursts and AGN. The next generation of infrared space telescopes (*Herschel, WISE, JWST*, and *SPICA*), together with ground-based sub-millimeter telescopes (*ALMA, CCAT, LMT*, etc.) will not only greatly expand our inventory of high-redshift LIRGs and ULIRGs, but also allow us to understand the physical conditions in these rapidly evolving galaxies at the earliest epochs.

**Acknowledgments.** We wish to thank the conference organizers for a stimulating meeting, and an enjoyable visit to Tokyo. We look forward to many more exciting results from the *AKARI* mission.

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